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Drought in the Breadbasket of America and the Influence of Oceanic Teleconnections

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DROUGHT IN THE BREADBASKET OF AMERICA AND THE INFLUENCE OF OCEANIC TELECONNECTIONS

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By

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ABSTRACT

From 1980 to 2020, drought events accounted for 11.4% of the billion-dollar disasters in the United States (U.S.) yet caused the second highest total amount in damages at $236.6 billion. With the average cost of a drought being upwards of $9.5 billion, these natural disasters can create serious problems in agriculture. Drought is defined as a period of below average precipitation that causes damage to agriculture and water supply. Previous research has linked drought events in the U.S. Great Plains to oceanic teleconnections in the Pacific and Atlantic basins, indicating the influence of the El Niño – Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO). This study looks to identify areas of the Great Plains where drought has the strongest correlations to ENSO, PDO, and AMO. The states studied are Iowa, Texas, Illinois, Minnesota, Texas, Nebraska, and Kansas because these rank as the second through seventh most agriculturally productive states in terms of crop and livestock production. Results show that most of this region displays a relationship between drought and the ENSO and PDO, with less of the region displaying a relationship with the AMO.

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INTRODUCTION

It goes without saying that the slow and steady, yet intense, nature of drought is what gives this natural disaster its costly edge. Since 1980, drought events have accounted for twenty-five of the 219 billion-dollar weather and climate disasters (11.4%), yet caused a total of $236.6 billion in damages, second only to tropical cyclones ($850.5 billion). The average cost of drought ranks at $9.5 billion, again second only to tropical cyclones ($22.4 billion) (NIDIS/NOAA, 2020). Three drought events, in 1980, 1988 and 2012, even surpassed the average tropical cyclone cost at $33.5 billion, $45.0 billion, and $34.5 billion, respectively (NOAA NCEI, 2020). In California, the year 2014 alone racked up $4 billion in damage due to extensive drought (Rodziewiez and Dice, 2020). However, severe drought events are not exclusive to the last forty years. The drought of the 1950's hit especially hard in the southern and central Great Plains, ranking as the worst Texas drought on record. At the time, people described it as not having a "public rain" for five or six years. The notorious 1930's drought gave rise to the "Dust Bowl" and affected nearly two-thirds of the country (Schubert et al., 2004). Conditions like these can create major problems for many parts of society including economics, hydrology, and tourism, but especially agriculture (Craft et al., 2013). Farmer losses from extreme drought can be upwards of 20% of production value for corn and wheat, while soybeans losses can reach 35%. Furthermore, the 2012 drought in the Midwest resulted in a loss of more than one-quarter of United States corn production by volume. These losses are largely from diminished yields and lower production during drought episodes (Rodziewiez and Dice, 2020). Being able to better predict when droughts occur, especially the severe ones, will help reduce the widespread impact of these costly natural disasters.

Drought, put simply, is characterized by a period of below average precipitation that causes damage to agriculture, ecosystems, and water supply (Goodrich et al., 2011). This persistent deficit of precipitation is usually a slowly evolving phenomenon which takes several months to reach its peak intensity and spatial extent and is not always associated with extreme heat. However, factors such as anomalously warm surface temperatures and persistent sunshine can work to quicken the evaporation process and trigger drought onset more quickly (Wang and Yuan, 2018). A particularly sensitive region to drought is the American Great Plains because of its national agricultural importance. What makes this region so sensitive is because the rainy season coincides with its growing season (Livneh and Hoerling, 2016). Lack of rainfall during this period can create serious problems like those seen in 1980, 1988, and 2012. A study focusing on the 2012 drought event in the Great Plains found that the key meteorological driver of drought in this region was soil moisture deficits driven by the lack of precipitation, in which soil moisture depletion was expedited by the record setting hot spring. They also identified a potential driver of these meteorological conditions in oceanic teleconnections (Livneh and Hoerling, 2016).

Defined by the National Centers for Environmental Information (NCEI), a teleconnection is "a spatially and temporally large-scale anomaly that influences the variability of the atmospheric circulation," (NOAA NCEI, 2021). The teleconnection identified by Livneh and Hoerling (2016) is the El Niño – Southern Oscillation (ENSO). It is an interannual, quasiperiodic, coupled mode of the tropical Pacific Ocean and the atmosphere, meaning fluctuations in sea-surface temperatures (SST) and atmospheric pressure shift on a nearly periodic timescale within a year. The two phases of ENSO are El Niño, characterized by abnormally warm SST in the tropical Pacific, and La Niña, characterized by abnormally cooler SST in the same region (Rajagopalan et al., 2000). Both phases exhibit strong seasonality and tend to develop during the late Northern Hemisphere spring/early summer and peak towards early winter. However, there is evidence that El Niño decays a lot faster after its peak than La Niña, which can persist through the following year and reintensify in the subsequent winter (Okumura et al., 2017). Other teleconnections have also been identified to modulate U.S. climate: the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO). The AMO is a temporally longer teleconnection than that of ENSO with a 65-to-80-year cycle in North Atlantic SSTs. The AMO oscillates between anomalously warm and cold temperatures, which mark the positive and negative phases, respectively. The PDO is like that of the AMO in that it has a longer time scale of around 50 years and represents a low frequency variability in SST in the northern Pacific. Alternatively, the warm phase of the PDO is associated with cooler sea temperatures in the north-central Pacific and warmer temperatures along the western coast of North America, while the cold phase displays an opposite pattern (Quiring and Goodrich, 2008). Interestingly, these teleconnections can also modulate and influence each other. A study by Cole and Overpeck in 2002 found that when the PDO is negative, La Niña phases are stronger and more stable. There is also evidence of AMO amplification from the PDO (Quiring and Goodrich, 2008). This modulation is important because it effects how the climate in various parts of the world is influenced by these teleconnections.

It has been found that regional drought likely reflects a consistent response to large-scale climate patterns, like those of teleconnections, meaning the nature of drought can change depending on the signals produced by these large-scale drivers. Researchers have identified strong relationships between ENSO and U.S. seasonal mean temperature and precipitation, which are the two major factors in drought initiation (Rajagopalan et al., 2000). More specifically, drier conditions are associated with negative SST anomalies in the tropical central and eastern Pacific (Hu and Huang, 2009). This region indicates ENSO and PDO influences. The PDO independently has been found to be covariable with U.S. summertime precipitation, but U.S. surface temperatures are covariable with the entirety of the Pacific Basin's SSTs (Schubert et al., 2004), which is another instance of both ENSO and PDO showing influence. Interestingly, this joint influence of ENSO and PDO on soil wetness anomalies is most noticeable and robust in the Great Plains. Moreover, climate anomalies in this region have been found to be intensified when the two teleconnections are in phase; La Niña and cold PDO are more likely to display anomalously dry conditions. Out of phase ENSO and PDO (La Niña and warm PDO or El Niño and cold PDO) therefore weakens the Great Plains relationship, and it has been found that without ENSO, PDO does not significantly alter climate in the Great Plains region. Because of the poor sampling of the PDO at interdecadal timescales (it has had only one positive and negative phase from 1950-2005), it is still unclear what impact PDO alone has on soil wetness conditions in the Great Plains (Hu and Huang, 2009). In addition to La Niña and cold PDO, the AMO has been found to have a relationship between warmer SSTs (positive phase) and below average precipitation in the central U.S. (Nigam et al., 2011; Veres and Hu, 2013). The seasonality of teleconnections can also influence temperature and precipitation more in some seasons than in others. The previous studies found that the AMO-precipitation relationship is strongest in the summer. La Niña has also been linked to precipitation deficits in both the winter (Okumura et al., 2017) and the summer (Hu and Huang, 2009) over the southern and central US, respectively. Consequently, Veres and Hu (2013) found that very dry conditions in the central and south-central U.S. are present with La Niña and the positive phase of the AMO. The temporal timescale of teleconnections can further create problems with regards to dryness. Because of the more persistent nature of La Niña, multi-year events tend to exacerbate dry soil moisture anomalies in subsequent years due to precipitation deficits in the winter and spring (Quiring and Goodrich, 2008). The AMO positive phase has also been linked to precipitation deficits in the fall and spring, in addition to summer, meaning Atlantic SSTs are influential in forcing multi-year dry periods (Nigam et al. 2011).

In fact, the extensive and severe 1930's and 1950's multi-year droughts occurred during the warm phase of the AMO (Quiring and Goodrich, 2008). Veres and Hu (2013) explains that the AMO accounts for 28% of the variation in U.S. drought, yet Nigam et al. (2011) found that in the 1930's drought, the AMO alone accounted for 55% of the observed anomalies. However, in the 1950's drought, the PDO accounted for over 50% of the observed signal. Together, these two teleconnections have been found to account for over half of the spatial and temporal variance in multidecadal drought frequency (Goodrich, 2007; Hu and Huang, 2009). Furthermore, many modeling studies have found that the joint effects of combined cold pan-Pacific SSTs and a warm North Atlantic have a stronger impact on droughts in the Great Plains than either by themselves (Pu et al., 2016; McCabe et al., 2004). This indicates the influence of AMO, PDO, and ENSO. Looking at ENSO individually, extensive research has been done exploring the relationship between the two phases and US droughts. Many articles provide evidence that Great Plains drought is linked to La Niña (Goodrich, 2007; Quiring & Goodrich, 2008; Pu et al., 2016). In fact, research shows a nearly threefold increase in severe low soil moisture conditions during La Niña compared to El Niño (Livneh and Hoerling, 2016). This helps to explain the significance of cold pan-Pacific SSTs in previous research, as it been previously mentioned that La Niña is strengthened by a cold PDO. Because of this relationship, it is important to mention that while droughts in the Great Plains tend to occur in La Niña years, La Niña alone does not necessarily lead to summer drought. Additionally, the dependence of Great Plains drought on La Niña is only significant in the winter, yet because of the longevity La Niña can exhibit and occasional reinforcement from the PDO, the decrease in precipitation particularly in the winter and spring can be maintained by other teleconnections and feedbacks until La Niña can exert a more defined influence again. Thus, drought in both the cool season and warm season can be linked to La Niña (Pu et al., 2016; Cole and Overpeck, 2002; Livneh and Hoerling, 2016).

The purpose of this research is to further explore the relationship between teleconnections and drought in the Great Plains. Which areas of the Central U.S. show the strongest correlations to teleconnection drivers during periods of drought? More specifically, we are looking to identify which teleconnections have the strongest relationships to drought in the most agriculturally productive states, since these areas are the most susceptible to severe drought impacts.

DATA & METHODS

Because of the well-defined relationship found in literature, the teleconnections used in this study are ENSO, PDO, and AMO. ENSO data was retrieved from the Climate Prediction Center (CPC; https://www.cpc.ncep.noaa.gov/), PDO data was retrieved from the National Centers for Environmental Information (NCEI; https://www.ncdc.noaa.gov/teleconnections/pdo/), and AMO data was retrieved from NOAA's Physical Sciences Laboratory (NOAA PSL; https://psl.noaa.gov/data/correlation/). ENSO is confined to the equatorial Pacific Ocean, and values from the Niño 3.4 region, which is roughly between 120°W and 170°E, were used to determine phases. This region gives a good measure of important SST changes and temperature gradients that act to produce changes in tropical convection (NCEI, 2021). An El Niño is defined as SST values greater than or equal to 0.5°C for three consecutive months in the Niño 3.4 region, while La Niña is defined as three consecutive months with values less than or equal to -0.5°C. For the PDO, ocean temperature anomalies are more widespread and found in the northeast and tropical Pacific Ocean. The warm phase displays warmer than average temperatures along the North American Coast and cooler than average temperatures in the interior Pacific, while the cold phase shows an opposite pattern. The AMO shows a similar pattern, but in the northern Atlantic Ocean. The warm phase is characteristic of warmer than average temperatures and the cold phase is characterized by cooler than average temperatures. Temperature anomalies here are slightly smaller than

ENSO's thresholds at ±0.4°C (Quiring and Goodrich, 2008). To identify drought period the Palmer Drought Severity Index (PDSI) was used. This standardized index uses temperature and precipitation data to estimate dryness. It is calculated using a water balance model that also takes evapotranspiration, runoff, recharge, and the effect of time into account (Palmer, 1965). The index spans from 10 to -10 indicating extreme wetness and extreme dryness, respectively (University Corperation for Atmospheric Research, 2021). While this index is useful for determining multi-month wet and dry spells, it is not as suitable for detecting short term events. A similar drought index is the Standardized Precipitation Index (SPI), which is more useful for looking at wet and dry periods at both short- and long-term time scales, but the SPI only uses precipitation inputs to calculate a value. It disregards outputs like evapotranspiration and runoff (University Corporation for Atmospheric Research, 2021). Using the PDSI dataset, a period of dryness (PDSI < 0) is considered a moderate drought when the PDSI drops below -2.0 for three consecutive months, while a major drought is six consecutive months of PDSI below -2.0. The drought ends when the PDSI becomes positive again (Goodrich et al., 2011; Goodrich, 2007; Craft et al., 2015). To classify drought events, they were categorized based on when the drought started: in the boreal warm season or the boreal cool season. The boreal warm season is defined as April to September, while the cool season is from October to March; these dates also coincide with the typical growing season (USDA NASS, 2010; Pu et al., 2016). Additionally, we classified any drought that lasted longer than twelve months as a multi-year drought.

Within the Great Plains and Midwest regions (Figure 1), six states were chosen based on their agricultural productivity: Illinois (IL), Iowa (IA), Kansas (KS), Minnesota

(MN), Nebraska (NE), and Texas (TX). In terms of total farm output, encompassing both crop and livestock, these six states rank as the second through seventh most productive states in the U.S. as of 2005 (IA, TX, IL, MN, NE, KS, respectively). California ranked number one overall but was left out due to spatial inconsistencies and climatic differences from the rest of the states. There is also a spatial inconsistency compared to the rest of the states studied. Looking specifically at livestock production, Iowa and Texas rank as first and second in productivity, with Nebraska, Minnesota, and Kansas at fifth, sixth, and seventh, respectively. Total crop output has all states but Kansas in the rankings at second through sixth: IA, IL, MN, TX, and NE, respectively (Wang et al., 2020).

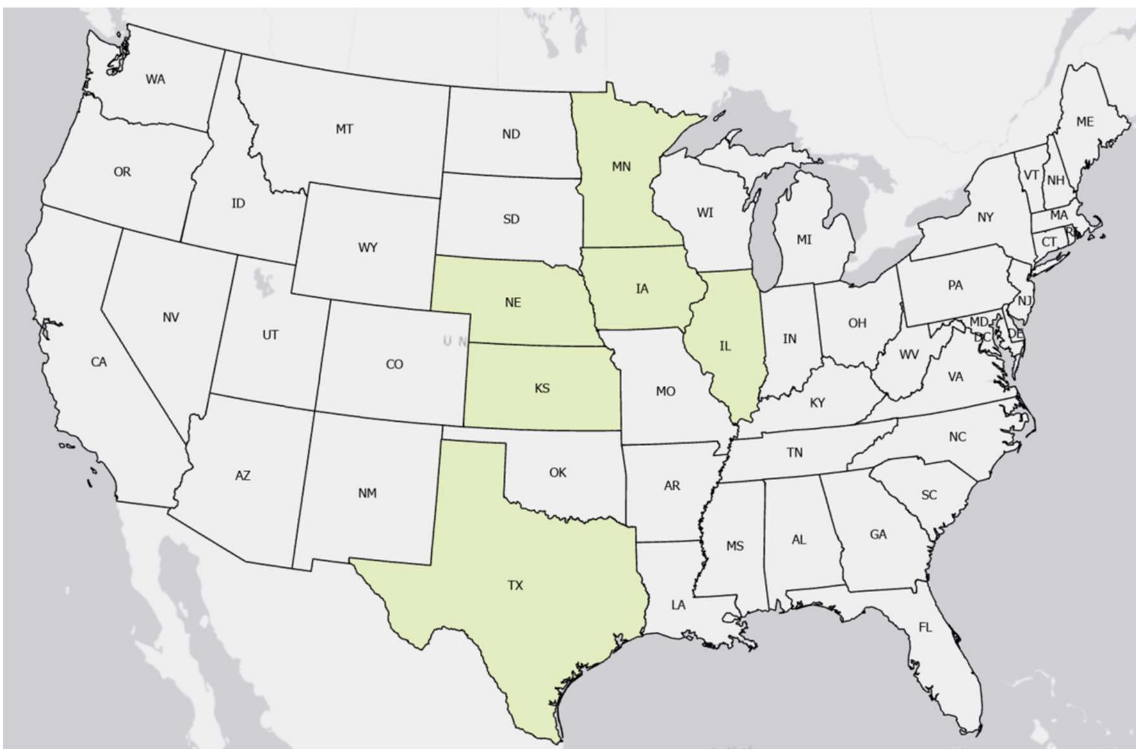

Figure 1: A map showing the study area with respect to the rest of the United States.

Monthly drought data from 1950 to 2019 was downloaded for each climate division in the states listed above and entered into Excel. Climate division data was used because of the availability of long-term time series data for popular drought indices, including the PDSI (Balling Jr. and Goodrich, 2007). For each climate division, drought periods were first identified based on their respective PDSI values. For each period, the average strength, maximum strength, and duration was calculated. Next, monthly teleconnection indices for ENSO, PDO, and AMO were introduced, and positive and negative phases were identified. To determine relationships between drought and teleconnection phase, the difference in means test (t-test) was used. Monthly PDSI values and their associated monthly teleconnection values were then sorted into two sections: drought and non-drought, meaning all months of drought and months of non-drought from 1950 to 2019 were separated into two sections. The Two-Sample t-Test Assuming Unequal Variances in Excel was used to determine if the mean teleconnection value for ENSO, AMO, and PDO, respectively, were different during periods of drought versus non-drought. The null hypothesis was that there is no difference between the average teleconnection value during months of drought and non-drought, while the alternative hypothesis stated there is a difference. If the two-tailed p-value was less than 0.05, then the null hypothesis was rejected, and we could assume there was a difference in the mean teleconnection value between periods of drought and non-drought.

RESULTS

a. *Drought*

The first step in the analysis is to look at drought occurrence in each state from 1950 to 2019. This gives us a look at how drought varies spatially across the study area and the characteristics of the drought within the region. For each climate division (CD), the total number of droughts, the average strength and duration of the droughts, and a running tally of the season in which droughts initiated and the number of multi-year droughts were recorded from PDSI data.

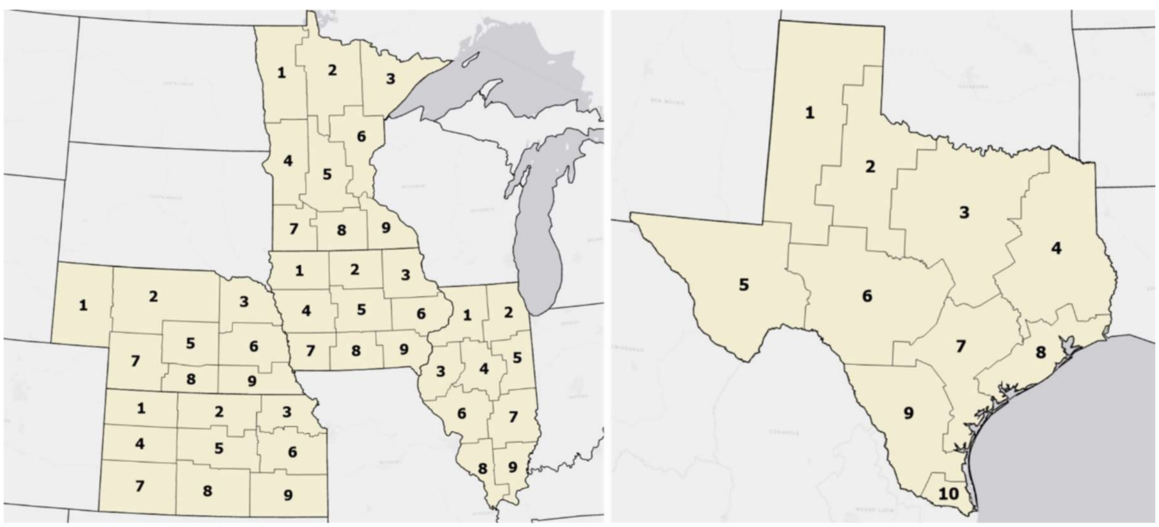

Figure 2: A map showing the location of each climate division for each state in the study.

i. Illinois

Table 1 displays the drought statistics for the nine climate divisions in Illinois. The average strength has PDSI values between -2.75 and -3. The strongest droughts on average were found in CD2, in the northeast corner of the state, at -3.30, which interestingly is also the location of the shortest average duration and on the lower end of the multiyear drought totals. The average duration collectively is also more variable across the state, ranging from 8.58 months to 16.90 months. As seen in Figure 2 and Table 1, the longest durations are consistently found in climate divisions that border the Mississippi River: CD3, CD6, and CD8. CD6, which had the highest average duration at 16.90 months, had the most multiyear droughts as well at five events; however, it also had the third lowest average strength of drought at -2.82, indicating longer but weaker droughts overall in this region. The number of droughts initiated in each season is nearly even except for CD4, which had 70% of its droughts begin in the cool season.

Table 1: Drought Statistics for Illinois. Duration is in Months.

Illinois						
	Total Droughts	*Avg. Strength*	*Avg. Duration*	*Cool Season*	*Warm Season*	*Multi-Year*
CD1	11	-3.17	10.82	5	6	3
CD2	12	-3.30	8.58	6	6	3
CD3	12	-2.91	13.92	6	6	4
CD4	10	-2.95	11.40	7	3	3
CD5	10	-2.96	11.50	5	5	2
CD6	10	-2.82	16.90	5	5	5
CD7	12	-2.80	10.50	6	6	2
CD8	9	-2.89	14.00	5	4	3
CD9	9	-2.77	12.89	5	4	2

ii. Iowa

Iowa had a similar number of total droughts as Illinois at around ten droughts, as seen in Table 2. The total number of droughts remains consistent across the Hawkeye State, hovering at around ten droughts over the 70-year period. The average strength also remained relatively consistent with PDSI values hovering around -3. The average duration of droughts in Iowa lasted about 12 months, but droughts in CD9 and CD1 lasted three and five months longer, respectively. Interestingly, these two climate divisions also had the highest number of multiyear drought events at five and seven, respectively. They are also found at opposite corners of the state, as seen in Figure 1. CD1, located in the northwest corner of the state with both the largest average duration and most multiyear droughts, also recorded the highest average strength at a PDSI of -3.60. Drought initiation in the boreal warm and cool seasons remained relatively even across the climate divisions, with only CD2 in the north-central part of the state showing a more significant difference of 66.67% of droughts initiating in the cool season.

Table 2: Drought Statistics for Iowa. Duration is in Months.

Iowa						
	Total Droughts	*Avg. Strength*	*Avg. Duration*	*Cool Season*	*Warm Season*	*Multi-Year*
CD1	9	-3.60	17.11	5	4	7
CD2	9	-3.11	14.44	6	3	3
CD3	10	-2.85	12.30	5	5	4
CD4	10	-3.20	12.00	5	5	4
CD5	12	-3.25	11.08	5	7	4
CD6	12	-3.13	11.67	6	6	4
CD7	11	-2.86	11.18	6	5	3
CD8	10	-3.09	13.60	6	4	2
CD9	11	-2.85	15.09	5	6	5

iii. Kansas

From Table 3, we can see that drought characteristics begin to change from Iowa and Illinois. Total droughts remain similar with an average of around eleven drought events since 1950. The exception is CD7, located in the southwest corner of the state, with only seven droughts. Average strength continues to hold steady around a PDSI value of -3 as well, ranging from -2.71 in CD2 to -3.23 in CD9. Kansas also displays the widest range in drought duration of all the states analyzed: 11.17 to 25.14 months! Interestingly, the climate division with the longest duration of droughts is also the same one with the smallest number of total droughts: CD7. This climate division also records the second weakest average strength of droughts at -2.73. CD7 also has the most multiyear droughts of all the climate divisions at five. This makes sense, because climatologically, the western half of Kansas is drier than the eastern half of the state. This environment makes it conducive for droughts to persist longer than droughts in the rest of the state. Longer-lived droughts will reduce the total number of droughts that occur, simply because they are persisting longer over time. On the other hand, the climate division with the shortest average duration, CD6, also records the most total droughts in the state at twelve. However, there was only one multiyear drought recorded for the climate division. CD6 is found in the far eastern part of the state, opposite CD7. As previously mentioned, the eastern half of Kansas is climatologically wetter, and this explains why droughts do not last as long but develop more often. These droughts lack persistence over time, giving the opportunity for more individual drought events to develop. Looking at the seasonality of drought initiation, Kansas droughts show a strong favor towards warm season initiation, with six out of nine climate divisions having more than 75% of their droughts start in this season. CD7 specifically sticks out as having 0% of droughts occur in the boreal cool season during the entire 70-year period.

Table 3: Drought Statistics for Kansas. Duration is in Months.

Kansas						
	Total Droughts	*Avg. Strength*	*Avg. Duration*	*Cool Season*	*Warm Season*	*Multi-Year*
CD1	10	-3.04	14.90	2	8	4
CD2	11	-2.71	18.55	2	9	4
CD3	11	-3.12	14.82	5	6	5
CD4	11	-2.60	16.82	2	9	4
CD5	12	-3.10	12.67	3	9	3
CD6	12	-3.09	11.17	2	10	1
CD7	7	-2.73	25.14	0	7	5
CD8	10	-2.93	15.40	5	6	4
CD9	10	-3.23	13.40	5	5	2

iv. Minnesota

Minnesota begins to show more variance in total drought across the state than the previous three. In fact, it has the most variability in drought occurrence than any other state with a range of seven droughts, as seen in Table 4. CD8, in the southernmost part of the state, holds the fewest events at seven, while CD3, in the far northeast corner of the state, had the most at fourteen. Similar to what we saw in Kansas, CD3 ended up with the shortest average drought duration at just under nine months, while CD8 had the longest average duration at almost sixteen months! Even more interestingly, CD8 had less multiyear droughts than CD3, at three and four, respectively! Even then, five multiyear events was the maximum for Minnesota, with two being the minimum. As for average strength, CD8 displayed the strongest droughts at an average PDSI value of -3.28. The weakest droughts were found in CD5 at -2.93, so we can see average strength continues to revolve around the -3 value. The seasonality of drought initiation also showed some interesting characteristics. Most climate divisions had an about equal split between boreal warm and cool season initiation, but CD5 only had 33% of droughts start in the boreal warm season, indicating that most droughts started in the cool season. CD7 had a similar pattern with only 36% of droughts materializing during the warm season. These two climate divisions were the only two out of nine that had the majority of droughts begin in the cool season and are both found in the southern half of the state.

Table 4: Drought Statistics for Minnesota. Duration is in Months.

Minnesota						
	Total Droughts	*Avg. Strength*	*Avg. Duration*	*Cool Season*	*Warm Season*	*Multi-Year*
CD1	12	-3.17	11.17	6	6	5
CD2	13	-3.02	10.23	7	6	5
CD3	14	-3.14	8.93	5	9	4
CD4	8	-3.13	11.63	3	5	2
CD5	9	-2.93	14.44	6	3	4
CD6	12	-3.03	11.00	6	6	4
CD7	11	-2.98	15.64	7	4	5
CD8	7	-3.28	15.86	3	4	3
CD9	9	-3.11	12.67	4	5	4

v. Nebraska

Nebraska displayed similar characteristics to that of Kansas, shown in Table 5. Total droughts averaged around ten, while the average strengths are mostly above -3. The average duration, however, is consistently longer than the droughts we have studied so far. All eight climate divisions have durations of thirteen months or longer, with the longest being twenty-two months in CD5. Almost two years! Interestingly, CD5 did not have the most multiyear droughts: it only had four events, while CD1 had the most at seven. However, CD1's average duration is only the third longest at just over 18.5 months. Seasonality closely resembled Kansas', with five climate divisions recording more than 70% of their droughts initiating in the warm season. Moreover, CD5 had 100% of droughts occur in the warm season! The rest showed an equal distribution between the two.

Table 5: Drought Statistics for Nebraska. Duration is in Months.

Nebraska						
	Total Droughts	*Avg. Strength*	*Avg. Duration*	*Cool Season*	*Warm Season*	*Multi-Year*
CD1	11	-3.05	18.64	2	9	7
CD2	10	-3.20	14.80	3	7	5
CD3	7	-3.63	15.86	3	4	2
CD5	7	-3.24	22.00	0	7	4
CD6	10	-3.08	13.00	4	6	3
CD7	10	-2.93	16.40	2	8	5
CD8	7	-2.86	20.00	2	5	4
CD9	12	-2.82	14.17	5	7	5

vi. Texas

Texas, being somewhat of an outlier geography-wise from the rest of the states in this study, displayed some different characteristics than the rest. Table 6 displays those characteristics. Texas climate divisions consistently had the most droughts, with the least being eleven and the most being sixteen. However, the average strength of those droughts are consistently the weakest among the six states with six climate divisions seeing an average strength below a PDSI of -3. The strongest droughts occurred in CD7, in the south-central part of the state, with a PDSI value of -3.47, however. This division also recorded the longest average duration of drought events at a little over twenty-two months. Interestingly, CD7 also had the lowest number of total droughts at eleven. There were also six multiyear events in CD7, which is tied for the third most, but is beat by seven events in CD9 and eight events in CD10, both in the southernmost part of the state. Additionally, the climate division with the shortest average duration, CD3 in the north-central part of the state, also recorded the most droughts overall at sixteen. Contrasting from the rest of the states, the seasonality of drought initiation favors the cool season rather than the warm season: five out of the ten total climate divisions recorded more than 60% of droughts initiate in the boreal cool season. Only one climate division, CD9, had the majority of droughts begin in the warm season at 64% of events. The remaining four had an about equal split.

Table 6: Drought Statistics for Texas. Duration is in Months.

Texas						
	Total Droughts	*Avg. Strength*	*Avg. Duration*	*Cool Season*	*Warm Season*	*Multi-Year*
CD1	14	-2.73	15.14	9	5	4
CD2	15	-2.87	15.73	10	5	3
CD3	16	-3.06	13.56	11	5	5
CD4	13	-2.90	16.46	6	7	6
CD5	13	-2.70	22.15	8	5	5
CD6	14	3.04	16.86	8	6	5
CD7	11	-3.47	22.27	7	4	6
CD8	11	-3.06	17.55	6	5	5
CD9	14	-2.88	20.00	5	9	7
CD10	15	-2.85	19.87	8	7	8

b. Teleconnections

Following the drought analysis, I then brought in teleconnection values to determine if there was a significant difference in the teleconnection values of ENSO, PDO, and AMO between periods of drought and non-drought (ND).

i. Illinois

Looking first at Illinois, Table 7 shows five out of nine climate divisions had significant p-values for ENSO: CD2, CD5, CD6, CD8, and CD9. The mean ENSO phase value for months of drought in each division fell below -0.10, indicating that during periods of drought, it is more likely to be during the La Niña phase in these regions. ND months in these same climate divisions had mean values in the neutral to very weak El Niño range. Rather, this means that periods of ND can occur with any ENSO phase. As for the PDO, again five climate divisions had significance: CD1, CD5, CD6, CD8, and CD9. We can see that four of those climate divisions are also shared with ENSO significance. Interestingly, looking at the means, they show that both periods of drought and ND are likely to occur during the negative phase of the PDO; however, what makes the difference significant is the fact that droughts are more often seen during periods of *strong* negative PDO. Every mean PDO value for drought in the significant climate divisions were less than -0.50. The AMO, however, is a much different story compared to ENSO and PDO; only one climate division had significance: CD6. Here, the mean AMO value lay in the neutral/very weak positive phase, indicating that droughts in CD6 are also more likely to be seen during a positive AMO phase. ND periods displayed a mean value in the neutral phase, again meaning that periods of ND can occur in both phases.

Table 7: Teleconnection Means for Periods of Drought and Non-Drought and the Corresponding P-Value in Illinois

Illinois									
	ENSO			*PDO*			*AMO*		
	Drought Mean	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*
CD1			0.12	-0.55	-0.33	**0.05**			0.39
CD2	-0.13	0.06	**0.03**			0.21			0.96
CD3			0.12			0.10			0.06
CD4			0.20			0.75			0.65
CD5	-0.23	0.07	**0.00**	-0.57	-0.33	**0.04**			0.64
CD6	-0.21	0.09	**0.00**	-0.54	-0.32	**0.03**	0.04	-0.02	**0.00**
CD7			0.75			0.19			0.23
CD8	-0.19	0.07	**0.00**	-0.76	-0.29	**0.00**			0.40
CD9	-0.17	0.06	**0.01**	-0.77	-0.30	**0.00**			0.13

ii. Iowa

Table 8 shows the teleconnection results for Iowa. Upon first glance, we can see that there are more climate divisions with significant relationships compared to Illinois. All nine climate divisions have significant p-values with ENSO phase. Each had the mean ENSO phase during drought trending towards the La Niña range, with all values less than or equal to -0.12. Interestingly, unlike Illinois which had ND mean teleconnection values near neutral, Iowa had ND means slightly greater than 0.05, which shows a tendency towards El Niño. The PDO showed significant relationships with all climate divisions except for one: CD8. Much like in Illinois, each significant climate division had both periods of drought and ND had teleconnection means associated with negative PDO, but drought periods had much stronger negative PDO means: all values were near -0.60, while ND values were half that, near -0.30. There were only two climate divisions with significant AMO relationships: CD8 and CD9. Here, drought periods showed mean AMO values tendencies in the neutral to very weak positive phase, while ND periods had AMO values trend towards the neutral to weak negative phase.

Table 8: Teleconnection Means for Periods of Drought and Non-Drought and the Corresponding P-Value in Iowa.

Iowa									
	ENSO			*PDO*			*AMO*		
	Drought Mean	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*
CD1	-0.22	0.09	**0.00**	-0.62	-0.31	**0.00**			0.08
CD2	-0.12	0.06	**0.04**	-0.63	-0.32	**0.01**			0.17
CD3	-0.17	0.07	**0.01**	-0.61	-0.32	**0.01**			0.56
CD4	-0.28	0.08	**0.00**	-0.65	-0.31	**0.00**			0.95
CD5	-0.32	0.10	**0.00**	-0.67	-0.30	**0.00**			0.20
CD6	-0.19	0.08	**0.00**	-0.58	-0.31	**0.01**			0.77
CD7	-0.26	0.09	**0.00**	-0.61	-0.32	**0.01**			0.26
CD8	-0.13	0.07	**0.01**			0.12	0.05	-0.02	**0.00**
CD9	-0.16	0.08	**0.00**	-0.64	-0.30	**0.00**	0.02	-0.02	**0.03**

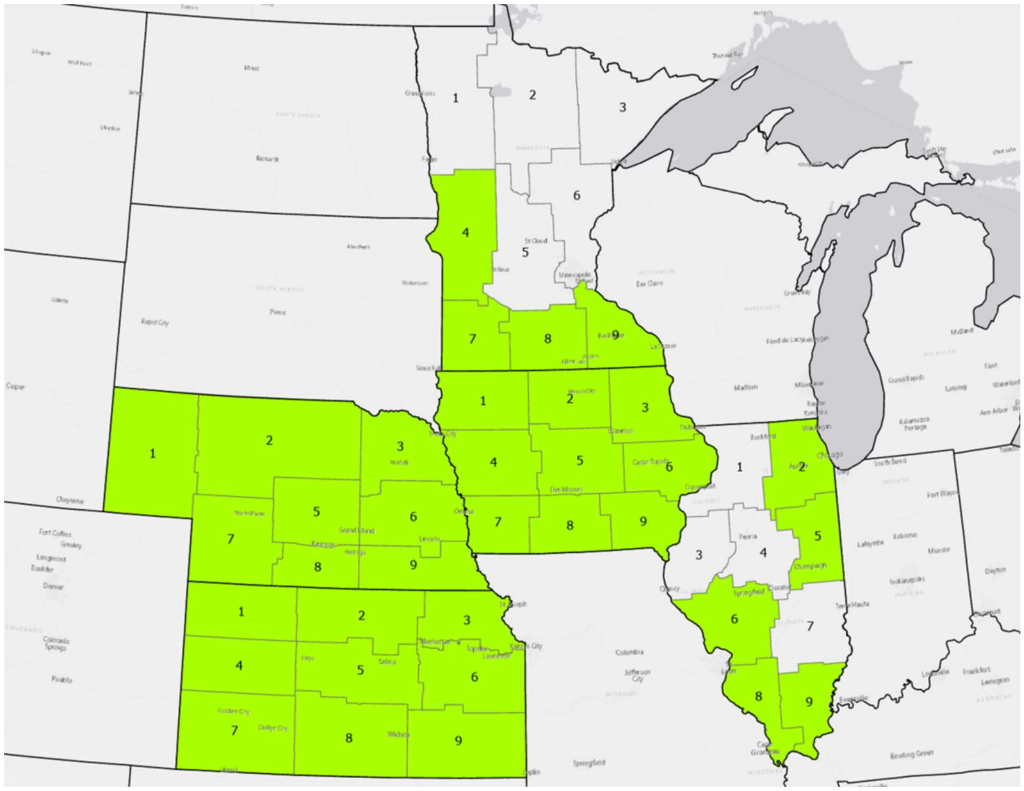

Figure 3: A map depicting the climate divisions with a p-value ≤ 0.05 for ENSO (Texas not shown).

iii. Kansas

Table 9 shows that all nine climate divisions in Kansas have significant relationships to all three teleconnections studied here. All climate divisions are significant with ENSO and PDO, and all but two are significant with AMO. Looking first at ENSO, each drought period for all nine climate divisions had ENSO values in trending towards La Niña, while ND periods had values again showing tendencies towards the weak El Niño range. PDO values for all nine climate divisions during drought once again fell to very strong negative PDO values. Some divisions, like CD7, CD8, and CD9, had mean PDO values as low as -0.90, -0.83, and -0.83, respectively! ND periods had much weaker negative PDO values around the -0.30 point. As for the AMO, we see more interesting results. Most of the climate divisions see mean AMO values during drought trending towards the neutral to very weak positive phase, while ND AMO values trend towards the neutral to very weak negative phase. However, CD3 shows the opposite. Here, during periods of drought, the mean AMO value shows tendencies towards the very weak negative phase at -0.04, while the ND AMO value is very neutral at 0.01.

Table 9: Teleconnection Means for Periods of Drought and Non-Drought and the Corresponding P-Value in Kansas.

Kansas									
	ENSO			*PDO*			*AMO*		
	Drought Mean	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*
CD1	-0.18	0.08	**0.00**	-0.66	-0.30	**0.00**	0.03	-0.02	**0.01**
CD2	-0.17	0.08	**0.00**	-0.67	-0.29	**0.00**			0.20
CD3	-0.15	0.08	**0.00**	-0.55	-0.32	**0.02**	-0.04	0.01	**0.00**
CD4	-0.13	0.07	**0.00**	-0.72	-0.27	**0.00**	0.02	-0.02	**0.03**
CD5	-0.20	0.09	**0.00**	-0.86	-0.24	**0.00**	0.04	-0.02	**0.00**
CD6	-0.12	0.07	**0.01**	-0.68	-0.29	**0.00**			0.20
CD7	-0.11	0.06	**0.01**	-0.90	-0.24	**0.00**	0.03	-0.02	**0.01**
CD8	-0.16	0.09	**0.00**	-0.83	-0.24	**0.00**	0.02	-0.02	**0.03**
CD9	-0.16	0.07	**0.00**	-0.83	-0.27	**0.00**	0.04	-0.02	**0.00**

iv. Minnesota

Minnesota displays results similar to that of Illinois, with sparce significance among the three teleconnections. Table 10 shows that only four climate divisions have significance with ENSO and PDO, and the AMO has even less with two divisions. ENSO values during periods of drought continue to display La Niña tendencies, while ND periods show El Niño tendencies. CD7 shows this to an extreme, with a drought ENSO value of -0.37, a strong trend towards La Niña, and a ND value of 0.12, a moderately strong trend towards El Niño. PDO displays similar traits as we have seen previously, with drought period PDO means running downwards of -0.60 or less, a strong negative PDO, and ND period means much weaker around -0.30. The AMO-significant climate divisions do not show as clear a picture. CD3 has the drought AMO mean trending towards the weak positive phase at 0.06, but CD7 shows the opposite with drought AMO mean trending towards the neutral to weak negative phase at -0.04. Both ND periods keep the AMO mean in the neutral phase, however.

Table 10: Teleconnection Means for Periods of Drought and Non-Drought and the Corresponding P-Value in Minnesota.

Minnesota									
	ENSO			*PDO*			*AMO*		
	Drought Mean	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*
CD1			0.09	-0.59	-0.32	**0.01**			0.39
CD2			0.75			0.21			0.09
CD3			0.12			0.83	0.06	-0.02	**0.00**
CD4	-0.15	0.06	**0.01**			0.58			0.06
CD5			0.30			0.60			0.80
CD6			0.78			0.98			0.23
CD7	-0.37	0.12	**0.00**	-0.74	-0.28	**0.00**	-0.04	0.00	**0.05**
CD8	-0.24	0.07	**0.00**	-0.81	-0.29	**0.00**			0.62
CD9	-0.23	0.07	**0.00**	-0.71	-0.31	**0.00**			0.31

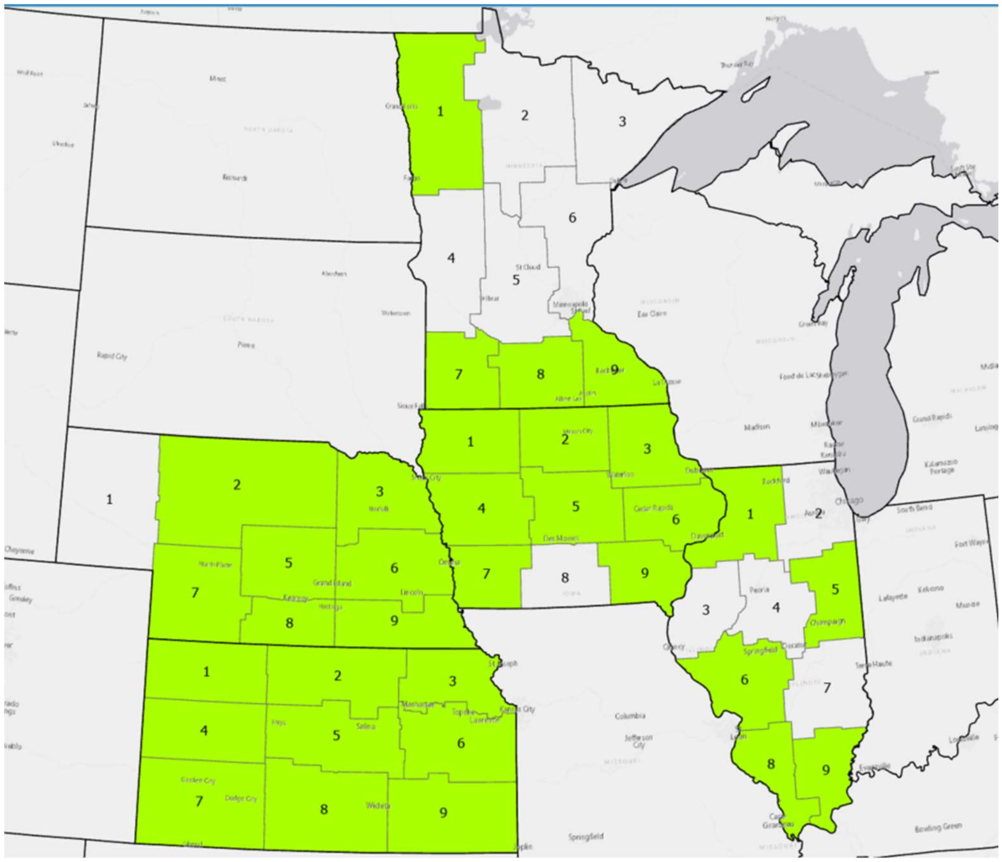

Figure 4: A map depicting the climate divisions with a p-value ≤ 0.05 for PDO (Texas not shown).

v. Nebraska

As seen in Table 11, Nebraska displays widespread significance across the state with ENSO and PDO, but less so with AMO. All eight climate divisions show ENSO significance. ENSO means during drought vary more than those in previous states, from -0.08 in CD1 to -0.35 in CD3 but all show La Niña tendencies as the predominant phase. ND periods vary much less and remain trending in the weak El Niño phase, but CD9 shows a stronger El Niño trend during ND periods at 0.10. All climate divisions but CD1 also show significance with the PDO, as seen in Figure 3. Periods of drought consistently display strong negative PDO values ranging from -0.59 to -0.78, with ND periods continuing to show weaker negative PDO phases around the common value of -0.3. The AMO only showed significance in CD5, CD7, and CD8. All three are once again consistent with drought period mean value showing tendencies towards the neutral to weak positive phase, with the strongest mean being in CD5 at 0.08. ND periods remained neutral.

Table 11: Teleconnection Means for Periods of Drought and Non-Drought and the Corresponding P-Value in Nebraska.

Nebraska									
	ENSO			*PDO*			*AMO*		
	Drought Mean	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*
CD1	-0.08	0.06	**0.01**			0.51			0.28
CD2	-0.14	0.07	**0.00**	-0.64	-0.30	**0.00**			1.00
CD3	-0.35	0.09	**0.00**	-0.78	-0.30	**0.00**			0.21
CD5	-0.09	0.06	**0.02**	-0.69	-0.29	**0.00**	0.08	-0.02	**0.00**
CD6	-0.26	0.09	**0.00**	-0.59	-0.32	**0.01**			0.93
CD7	-0.11	0.07	**0.00**	-0.73	-0.28	**0.00**	0.03	-0.02	**0.00**
CD8	-0.14	0.07	**0.00**	-0.77	-0.28	**0.00**	0.04	-0.02	**0.00**
CD9	-0.29	0.10	**0.00**	-0.68	-0.30	**0.00**			0.08

vi. Texas

With regards to all three teleconnections, Table 12 shows that nearly the entire state of Texas has significant relationships with all three. Only CD4 lacks a significant relationship with the AMO. Similar to CD9 in Nebraska, Texas ENSO values display vast differences between drought and ND periods. Drought ENSO means show tendencies steady in the La Niña phase, with values ranging from -0.18 to -0.35. ND periods, however, all have ENSO means trending in the El Niño phase, ranging from 0.12 to 0.18, which are the strongest El Niño values seen so far in this study. In a similar fashion, PDO values are more defined between drought and ND periods. Drought period PDO means record the strongest negative PDO values seen thus far, ranging from -0.91 to -1.04. ND periods, interestingly, still record a negative PDO value, but they are much weaker than what we have seen so far at around -0.12. The AMO, on the other hand, does not show as drastic a difference compared to other AMO values in other states. Drought periods continue to show AMO value tendencies in the weak positive phase. ND periods are continuously in the neutral to weak negative phase, revolving around a zero point.

Table 12: Teleconnection Means for Periods of Drought and Non-Drought and the Corresponding P-Value in Texas

Texas									
	ENSO			*PDO*			*AMO*		
	Drought Mean	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*	*Drought Mean*	*ND Mean*	*P-value*
CD1	-0.26	0.13	**0.00**	-0.99	-0.16	**0.00**	0.03	-0.02	**0.00**
CD2	-0.26	0.14	**0.00**	-0.97	-0.15	**0.00**	0.05	-0.03	**0.00**
CD3	-0.23	0.12	**0.00**	-0.94	-0.17	**0.00**	0.03	-0.02	**0.00**
CD4	-0.35	0.16	**0.00**	-0.91	-0.19	**0.00**			0.08
CD5	-0.18	0.14	**0.00**	-0.92	-0.10	**0.00**	0.05	-0.03	**0.00**
CD6	-0.27	0.16	**0.00**	-0.95	-0.12	**0.00**	0.05	-0.03	**0.00**
CD7	-0.32	0.18	**0.00**	-0.98	-0.11	**0.00**	0.04	-0.03	**0.00**
CD8	-0.32	0.14	**0.00**	-1.04	-0.16	**0.00**	0.02	-0.02	**0.04**
CD9	-0.26	0.17	**0.00**	-0.87	-0.12	**0.00**	0.05	-0.04	**0.00**
CD10	-0.16	0.13	**0.00**	-0.90	-0.09	**0.00**	0.07	-0.05	**0.00**

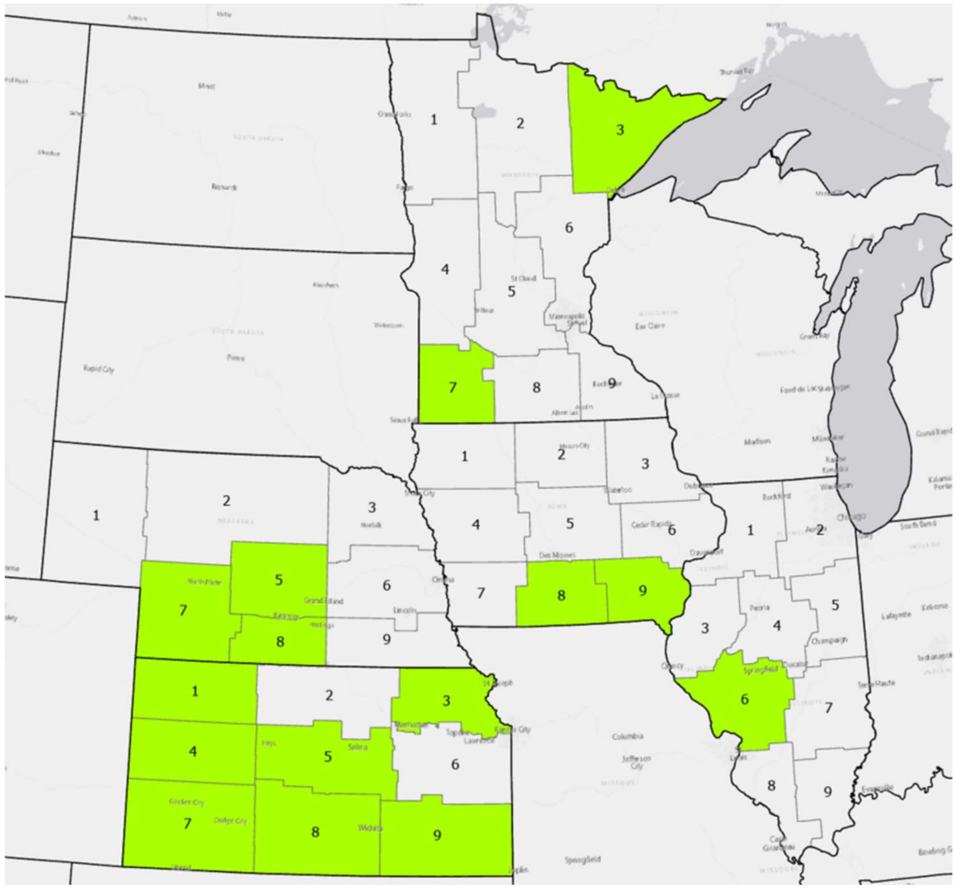

Figure 5: A map depicting the climate divisions with a p-value ≤ 0.05 for AMO (Texas not shown).

DISCUSSIONS

Figures 1, 2, and 3 all show the climate divisions that have a p-value of 0.05 or less when it comes to drought and ENSO, PDO, and AMO, respectively (Texas not shown since entire state is significant). This allows us to look at the spatial orientation of where drought occurrence has a significant relationship with each of the teleconnections. Looking first at the ENSO significance map (Figure 1), we see that the entirety of Iowa, Nebraska, and Kansas are statistically significant, as is Texas (Table 12). Illinois is more sporadic and only the southern half of Minnesota is significant. From Tables 6 – 12, we see that during drought periods for all significant climate divisions, the ENSO phase tends towards La Niña. What this tells us is that when droughts occur in these areas, they are more often seen during a La Niña than any other phase, but can still occur in any phase. Research supports this by showing that during La Niña when sea surface temperatures are cooler than average, drier conditions are more likely in the central Great Plains (Hu & Huang, 2009). This is because ENSO can modulate temperature and precipitation in this region (Rajagopalan et al., 2000), the two main drivers of drought. During La Niña, particularly in the winter, research has found that the cooler waters in the equatorial Pacific create anomalous sinking air over the equatorial Pacific. Another region of sinking air is also found near the American Southeast. This causes the Pacific jet stream to shift farther north towards Alaska and to cut down through the western U.S. before shifting back northward through the Northeast over the anomalous high in the Southeast. This pattern typically keeps anomalously warm air confined to the southern U.S., and more importantly redirects storm systems away from the area and towards the Upper Midwest (De Liberto, 2016; Jong et al., 2020). This pattern helps explain the widespread significance of Texas drought and the more sporadic nature of Illinois significance with La Niña; storms are redirected away from Texas leading to anomalously dry conditions in the state, especially during the winter, while precipitating storms are sent towards Illinois as seen in Figure 4. This is further supported by the drought statistics found in Table 6 which shows that half of the Texas climate divisions saw most of the droughts initiate during the cool season.

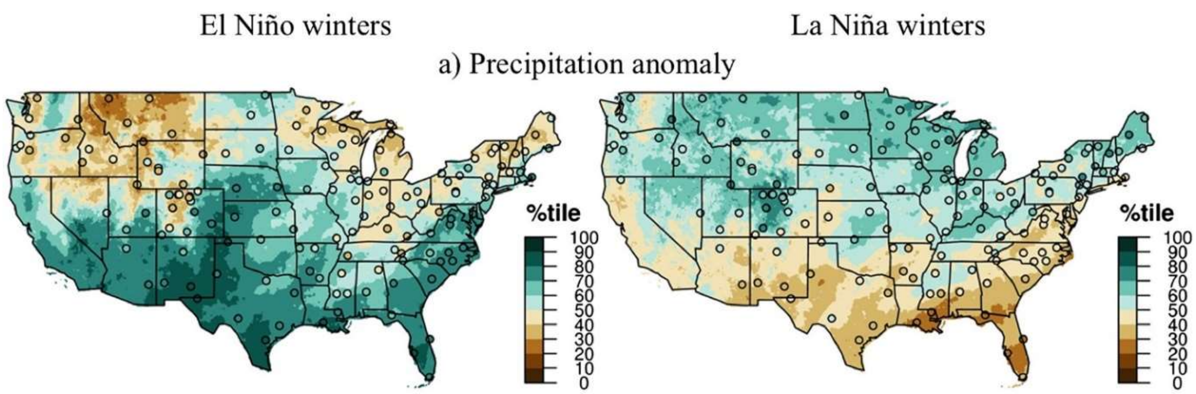

Figure 6: Map depicting El Niño and La Niña winter patterns across the U.S.

Furthermore, Jong et al. (2020) found that during the summers that had a developing La Niña, the poleward shift of the jet stream is accompanied by a larger, continental-scale anticyclone over the central U.S. This creates a barotropic environment over the region and is conducive to the development of hot and dry summers across the Great Plains due to the shifting of precipitating systems to the north and east. This setup helps explain the widespread significance we see in Kansas and Nebraska during the summer; Tables 3 and 5 both show that most climate divisions had the most droughts initiate during the warm season, with some even having all drought occurrences start in the warm season. Moreover, the Jong et al. (2020) article emphasizes that this setup usually occurs when El Niño is transitioning into La Niña or when the La Niña is developing. This study's results also point towards this idea, even though transition periods were not a focus of this study. For example, looking at CD1, CD5, and CD7 from Nebraska in Table 5, they all have at least 80% of their droughts initiate in the warm season. Looking at the corresponding Table 11, teleconnection analysis results show that these same climate divisions have the weakest La Niña tendency values during drought in the table (and even of all the climate divisions studied). These weaker La Niña values could be explained by the idea that during the summers in which these droughts occur, the La Niña is merely developing and not yet at its peak strength. A similar occurrence can be found in Kansas CD6 and CD7.

Next, Figure 2 focuses on the spatial significance pattern of the PDO and drought occurrence. PDO significance shows a similar spatial pattern to that of ENSO, which makes sense knowing that research has shown strong ties between the two teleconnections. All of Kansas is significant, Nebraska and Iowa are mostly significant save CD1 in Nebraska and CD8 in Iowa, the bottom half of Minnesota remains significant, and Illinois is still sporadic. The entirety of Texas is significant as well. It is important to reiterate here that research has found that the PDO and ENSO tend to "work together" when modulating climate in North America, including drought. Our results in Tables 7 – 12 show that both drought and non-drought periods occur during the negative phase of the PDO, however drought periods continuously occurred during strong negative PDO events. This can be explained by the fact that over the 70-year period in this study, there have been two cold phases (over 60% of months from 1950 – 2019 were cold PDO), but only one, extended warm period from about 1977 to 1999. With this in mind, the “strong” PDO values found during drought periods tell us that drought favors the negative phase, and that ND periods may favor a phase closer to neutral or even slightly positive.

It should be mentioned here that it has been found that without ENSO, the PDO does not significantly alter North American climate (Hu and Huang, 2009). However, research has shown that the PDO can influence the “strength and character of ENSO” (Birk et al., 2010). Hu and Huang (2009) go on to explain that both the ENSO and PDO generate a similar atmospheric circulation pattern across the Pacific and North America, meaning the phase of the PDO can suppress or enhance the effects of the ENSO phase. For example, the negative (or cold) PDO reinforces La Niña, which creates a cold tropical and extra-tropical Pacific and enhances the atmospheric pattern the La Niña can produce. This is important with regards to drought because a study done by Schubert et al. (2004) found that U.S. summer precipitation is covariable with the PDO on decadal timescales, but also found that U.S. temperatures are covariable with the entire Pacific basin. This means that negative PDO and La Niña are conducive for drought development in the Great Plains in both the warm and cool seasons. So much so, that it is during these phases that long-lived, multiyear droughts are most likely to occur due to the overlap in the La Niña and PDO areas of influence (Schubert et al., 2004). In terms of our results, this can be seen particularly well in Texas. Table 12 shows that both ENSO and PDO drought means are the strongest of all the states, and Table 6 shows that Texas had the most multiyear droughts of any state.

AMO results, as seen in Figure 3, tell a much different story. AMO significance is fewer and farther between, with the most widespread significance in Kansas with seven out of nine climate divisions showing significance, and Texas with nine out of ten showing significance. Similar to the PDO, the AMO is multidecadal and there have only been about two complete cycles since the beginning of the instrumentation record (Veres and Hu, 2013). Additionally, over long periods of time the AMO has displayed little variability, which explains why both the drought and ND averages for the AMO are so close together compared to the other teleconnections. However, the consistency of drought periods displaying a positive AMO value shows that drought, specifically in the southern Plains, does favor the positive, warm phase of the AMO. Research supports this and tells us that during the positive phase, the atmosphere below about 750 mb dries out during the summer. This leads to enhanced static stability in the atmosphere and makes it harder for convection to occur. Additionally, it has been found that negative vorticity is often found over this region, further inhibiting precipitation development (Veres and Hu, 2013). The results align with this by displaying the most widespread significance in Kansas and Texas.

CONCLUSIONS

This study looked at the relationships between drought and oceanic teleconnections in some of the most agriculturally productive areas in the United States. Using the difference of means t-test, drought, in the form of the PDSI, for each climate division was tested against monthly teleconnection values from 1950 to 2019 to identify which phases are significant with regards to drought occurrence. Results showed that drought favors the La Niña phase of ENSO, the negative phase of the PDO, and the positive phase of the AMO. These results align with the findings of previous research (Goodrich, 2007; Quiring and Goodrich, 2008; Pu et al., 2016, Livneh and Hoerling, 2016; Veres and Hu, 2013). However, there are caveats to how well these teleconnections can be used as a predictor of drought in the Great Plains and Midwest, specifically with multidecadal teleconnections like the PDO and AMO. A recent study by Mann et al. in 2020 discusses the lack of consistent evidence for long-term oscillatory signals that are more than just climatic noise. In simulations, they find no significant features within bi-decadal or multidecadal timescales that are not expected to simply be random noise. However, in historical observations there is evidence of a narrowband AMO signal around a 50-year period, but still no evidence for a bi-decadal PDO peak at around 15-20 years. Historical simulations also emphasize the North Atlantic, which is consistent with the AMO signature, but they found that the pattern is similar to the estimated response to sulfate aerosols produced though anthropogenic means. Positive AMO peaks align with periods of low concentrations over the North Atlantic, while the negative AMO peak in the 1980s aligns with a period of high aerosol concentrations. ENSO, on the other hand, shows up clearly in simulations and observations, further confirming its existence as a teleconnection.

Despite these caveats, future work on this topic would further explore the relationships between coupled teleconnection effects on drought to see how teleconnection phases work together to modulate drought. Additionally, further studies would focus more on the agriculture side of things, looking at how yields respond to drought driven by teleconnections versus drought driven by other processes, such as land-atmosphere feedbacks.

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